Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section), 89 (1991) 379–398
Elsevier Science Publishers B.V., Amsterdam

Global coastal hazards from future sea level rise

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(Received 6 December 1989; revised and accepted 7 June, 1990)

ABSTRACT

Gornitz, V., 1991. Global coastal hazards from future sea level rise. Palaeogeogr., Palaeoclimatol., Palaeoecol. (Global Planet. Change Sect.), 89: 379–398.

A rise of sea level between 0.3 and 0.9 m by the end of the next century, caused by predicted greenhouse climate warming, would endanger human populations, cities, ports, and wetlands in low-lying coastal areas, through inundation, erosion and salinization. The consequences of a global sea level rise would be spatially non-uniform because of local or regional vertical crustal movements, differential resistance to erosion, varying wave climates, and changeable longshore currents.

Although many factors can influence sea level, leading to a noisy record, various studies utilizing tide-gauge data find an average global rate of sea level rise of 1–2 mm/yr, over the last 100 years. This trend is part of a general rise over the last 300 years, since the low point of the Little Ice Age. Sea level rise may accelerate 3–8 times over present rates, within the next century.

The permanently inundated coastal zone would extend to a depth equivalent to the vertical rise in sea level. Major river deltas, coastal wetlands and coral islands would be most affected. Episodic flooding by storm waves and surges would penetrate even farther inland. Beach and cliff erosion will be accentuated. Saltwater penetration into coastal aquifers and estuaries could contaminate urban water supplies and affect agricultural production.

Research on relative risks and impacts of sea level rise on specific localities is still at an early stage. Development of a global coastal hazards data base, intended to provide an overview of the relative vulnerabilities of the world's coastlines, is described in this paper. To date, information on seven variables, associated with inundation and erosion hazards, has been compiled for the U.S., and parts of Canada and Mexico. A coastal vulnerability index (CVI) has been designed to flag high risk coastal segments. Preliminary results are presented for the eastern United States, as a test case.

Introduction

The greenhouse climate warming, caused by the atomospheric buildup of CO_2 and trace gases (Hansen et al., 1988; Pearman, 1988) could raise sea level by 0.3 m by 2050 and 0.6 m by 2100 (Meier, 1989; Oerlemans, 1989). Although significantly reduced from previous estimates (NRC, 1987), these figures still represent an increase of 3–8 times over present rates of sea level rise. Locally, increases could be still greater, depending on land subsidence factors. Accelerating sea level trends could seriously exacerbate erosion, inundation and salinization hazards, with increased risk to human life and property along low-lying coastal areas.

The effects of the worldwide sea level rise (SLR) will be spatially nonuniform, for several reasons. First of all, the global or eustatic change is superimposed on local vertical crustal movements. Areas where land is rising, due to glacial rebound (e.g. Fennoscandia, the Canadian shield), or tectonism (much of the Pacific coast of the Americas), will be at less risk than subsiding regions (such as the Mississippi and Nile deltas; the Low Countries). Secondly, the characteristics of any given coastline results from the interaction between lithology, landform,

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wave climate, longshore currents, and storm frequencies. Relative magnitudes of these variables change from place to place, which induce a non-uniform response of the coastline to SLR. Thus, the coastal vulnerability will vary spatially. *Coastal vulnerability* is the liability of the shore to respond adversely to a hazard. A *coastal hazard* is a natural phenomenon that exposes the littoral zone to risk of damage or other adverse effects. An *impact*, however, is the negative consequence(s) arising from the assumed SLR. Although sea level rise is emphasized in this paper, other factors such as winds, waves, and storm surges represent additional types of coastal hazard. Sea level rise is a global-scale, long-term hazard, which may, in the long run, inflict even greater damage than that of a hurricane. The intensity of "rapid-onset" hazards may also vary in response to global climate warming. [1] Because of the complexity of modeling the response of these hazards to climate change, how these will in turn alter coastal vulnerability lies outside the scope of this paper. However, rising sea levels will only exacerbate these effects.

Recent historical and projected sea level trends (± 100 years) are briefly reviewed in the next section. Processes changing the coastal zone during a period of rapid sea level rise are discussed in the succeeding section. Examples of recent investigations into potential adverse effects of SLR on coastal cities and ecosystems are presented. Finally, preliminary results from a coastal hazards data base are summarized for the eastern U.S. Ultimately, this inventory of erosion and inundation hazards will classify the relative vulnerability of the world's coastlines to SLR, in order to select high risk areas for more detailed, higher resolution analysis, and to integrate with other data sets monitoring global environmental change, such as those planned for the International Geosphere–Biosphere Program.

Sea level trends—recent past and near-future

The detection of sea level change is complicated by the large number of factors which influence sea level. Short-term changes (100–150 years) in sea level are obtained from tide-gauge records, which are geographically biased toward the northern hemisphere, and often consist of time series which are too short or too broken to be useful. Furthermore, the records exhibit variability produced by tides, ocean–atmosphere effects such as the El Niño/Southern Oscillation (ENSO), and vertical land movements (including glacial rebound, neotectonism, sedimentation and compaction, and subsurface fluid withdrawal). Thus, sea level changes may reflect real changes in the fluid-volume of the oceans (the *eustatic* change), as well as changes in land elevation on local to regional scales, or shifts in ocean currents. For these reasons, some scientists have questioned whether an average of tide-gauge measurements can represent the eustatic trend (Pirazzoli, 1986, 1989).

Nevertheless, many studies of global mean sea level changes (≤ 100 years) yield rates between 0.5 and 3 mm/yr, with most reported values ranging between 1–2 mm/yr. (For a comprehensive review, see Pirazzoli, 1989; and a status report, Warrick and Oerlemans, 1990, also Fig. 1). The most recent studies have attempted to filter out long-wavelength crustal movements by using ^{14}C-dated paleosealevel indicators (Gornitz and Lebedeff, 1987) or geophysical modeling (Peltier and Tushingham, 1989). Douglas and Herbrechtsmeier (1989) have found a trend of 1.6 ± 0.6 mm/yr, after screening out stations for wind forcing effects, as well as correcting for glacial rebound.

In spite of noisy data, spatially and temporally coherent rises in sea level can be recognized, especially for better-documented regions with large station populations. More significantly, rates of sea level rise over the last 100 years, in general, exceed those of the late Holocene (the

[1] Hurricane intensity may increase in a double-CO_2 world (Emanuel, 1987). Areas subject to the strongest hurricanes (e.g. Bangladesh and the U.S. Gulf Coast) will also be especially vulnerable to SLR for reasons discussed in the text.

last 5000 years), and especially those of the last 2000–3000 years. There is also some suggestion of a modest increase in SLR (0.4 mm/yr) in Northwest Europe, during the last 100 years, as compared with the previous 100 years (Woodworth, 1990). It is very unlikely that these differences represent a recent change in the rate of land subsidence or sediment compaction, except in cases of localized fluid withdrawal (Gornitz, 1990a).

Eustatic sea level rise over the next century will be the sum of individual contributions from thermal expansion of sea water and ice melting from alpine glaciers, polar ice sheets (Greenland and Antarctica), and possible instability of the West Antarctic Ice Sheet (WAIS).

The latest calculations suggest that polar ice sheets will contribute less to future SLR than previously estimated. The Antarctic, in contrast to Greenland and most mountain glaciers, is presently so cold and dry, that increasing temperatures in the future will enhance snow accumulation over ablation, leading to a negative SL contribution (Oerlemans, 1989). These results are based upon calculated changes in saturated vapor pressure over ice, as well as correlations between observed temperatures and snow accumulation (Meier, 1989). Finally, re-examination of ice melting processes suggest the disintegration of WAIS will take several centuries, at least (Budd, 1987).

Summarizing these various processes, Meier (1989) estimates that by 2050, thermal expansion of the oceans will contribute 0.2 ± 0.1 m, small glaciers 0.16 ± 0.14 m, Greenland 0.08 ± 0.12 m, the Antarctic -0.3 ± 0.2 m, and other

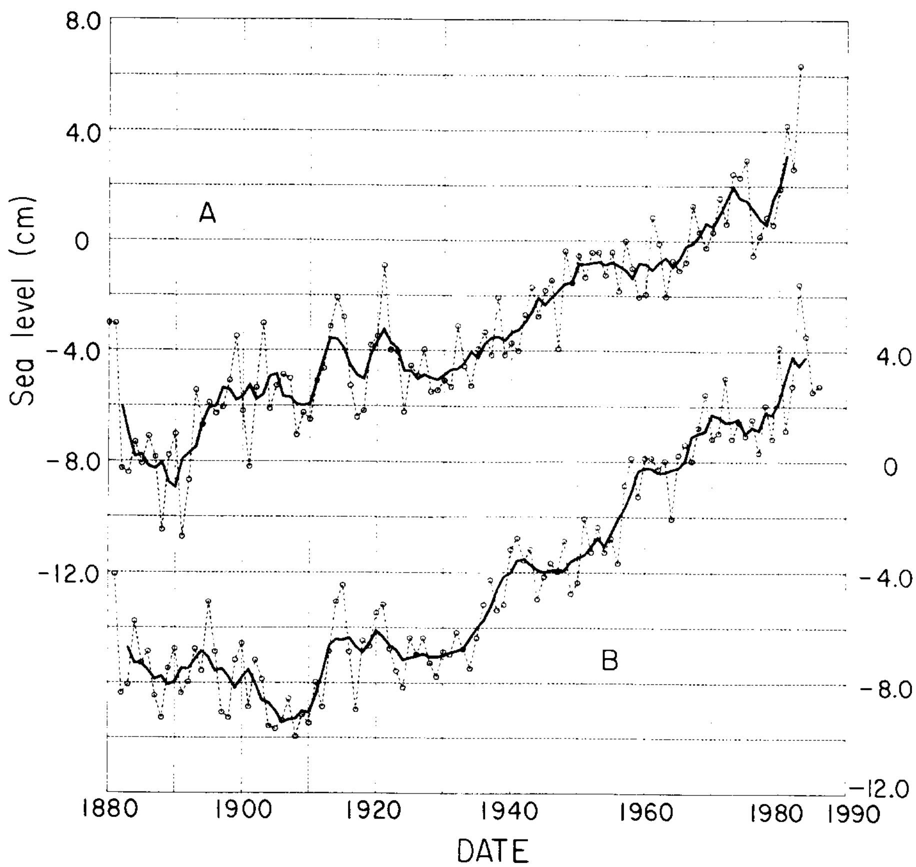

Fig. 1. Global mean sea level rise over the last century. The baseline is obtained by setting the average for the period 1951–1970 equal to zero. The dashed line represents the annual mean and the solid line represents the 5-year running mean. The top curve (A) is modified from Gornitz and Lebedeff (1987), and the bottom curve (B) is from Barnett (1988).

effects 0.2 ± 0.3 m or a total SLR of 0.34 ± 0.42 m. Although Oerlemans (1989) projects a similar increase of 0.33 ± 0.32 m by 2050, reaching 0.66 $\pm$ 0.57 m by 2100, in his model, the contributions from glaciers and thermal expansion are comparable, whereas those from Antarctica and Greenland largely cancel.

Given the great uncertainties due to the incompleteness of our knowledge of processes and observations, these projections can only be viewed as tentative scenarios of sea level rise, against which coastal hazards must be assessed.

Responses of the shore to accelerated sea level rise

The following are the major processes that will affect the coastal zone, during a period of accelerated sea level rise: (1) inundation, both permanent and episodic, (2) increased erosion, and (3) salt water intrusion of estuaries and aquifers. These are now briefly discussed in turn.

Inundation

Permanent inundation, by an amount corresponding to the vertical increase in relative mean sea level, will affect an area which depends on the local gradient. Low gradient coastal landforms most susceptible to inundation include beach ridge and chenier plains, deltas, mudflats, estuaries, lagoons, and bays. In the U.S., this includes marsh areas along the Atlantic Coastal Plains, much of the Florida Everglades, and the Gulf Coast. Other high risk areas, elsewhere, include the estuaries of eastern U.K., the European Low Countries, the Southern Baltic, and major river deltas, such as those of the Nile, the mouths of the Indus, Ganges–Brahmaputra and Irrawaddy Rivers, and the Chao Phraya River, in southern Asia. Within the next 100 years, 26% of the land in Bangladesh and up to 21.5% of habitable land in the Nile Delta could be lost, under SLR scenarios that include local subsidence and damming (Milliman et al., 1989). The threat to Bangkok is acute; local subsidence due to groundwater pumping has reached up to 13 cm/yr in recent decades (ibid). In Indonesia, the eastern coast of Sumatra, and large sections of coastal Borneo (Kalimantan) will face flooding. Other highly populated deltas and coastal plains are at risk; however, many of these areas (e.g. Amazon, Orinoco, Niger Deltas, etc.) are still relatively underpopulated.

Coastal wetlands will be among the most severely affected ecosystems, since these form largely in the intertidal zone. The response of a salt marsh to rising sea level depends on the relative rates of submergence vs. vertical accretion or sedimentation. A marsh may maintain its areal extent or even grow in the face of SLR, if sedimentation rates at least match submergence rates. Even so, the marsh (or mangrove in the tropics) will extend landward, as the upland edge is colonized by inland migrating marsh vegetation. However, this landward translation of ecological zones might be hindered by an increase in slope upland, as well as by economic development of the interior.

In the U.S., present rates of marsh accretion are generally keeping pace with present SLR, except for parts of Louisiana and portions of the Chesapeake and Delaware Bays (NRC, 1987). Around 140 km^2 of Louisiana wetlands are inundated annually (EPA, 1987). This loss is aggravated by a high submergence rate (~ 10 mm/yr), which, in part, is due to the curtailment of sediment supply from the Mississippi River, in recent decades, because of upstream dams, channels and levees. The construction of dikes along the Mississippi River and canals in the wetlands, have accelerated saltwater intrusion into abandoned delta lobes, thereby destroying the vegetation cover and exposing the area to increased erosion (Day and Templet, 1989). The high subsidence rate may be also exacerbated by oil and gas pumping.

Under extremely high rates of SLR (2.2 m by the year 2100), 73% of all U.S. wetlands existing in 1975 would be inundated, based on a sample of 57 coastal sites, occupying 485,000 hectares (Armentano et al., 1988). This loss could be reduced to 56%, by the formation of new wetlands further inland. Under a lower SLR scenario (1.4 m), a 40% inundation could be reduced to 22%, by inland migration of wetlands.

In the tropics, clearing of coastal mangrove swamps and forests, such as the 6000 km^2 Sundarban mangrove forest in southwestern Bangladesh, could accelerate erosion trends and expose the interior to damaging storm surges. This forest may be inundated by even a 1 m SLR. Another highly vulnerable ecosystem is freshwater peat bogs, bordered by mangroves, which occur in many parts of Indonesia.

Many coral islands have an average elevation of only 1.5–2 m above present sea level, and are therefore at risk to inundation. The ability of corals to keep up with SLR depends on the relative rates of coral reef growth. If the rate of SLR approaches 10–12 mm/yr, which is close to the maximum calcification rates (Hopley and Kinsey, 1988; Buddemeier and Smith, 1988), even fast-growing coral species may begin to lag behind and become progressively submerged. Furthermore, coral growth may be retarded at sea surface temperatures above 30°C, which may become prevalent in tropical oceans, in a high CO_2 world. Already, within the past few years, widespread severe coral "bleaching" episodes have occurred, which have been linked to the general global warming trend of the 1980's (Bunkley-Williams and Williams, Jr., 1990). If sea-surface temperatures continue to rise in the future, such bleaching events may become even more persistant, inhibiting coral growth, and tipping the balance in favor of submergence. The survival of coral islands will depend on whether or not living coral growth rates can match SLR and sufficient coral rubble can accumulate to maintain protective storm ridges. Potentially vulnerable islands include Indian Ocean islands, such as the Maldives, and many Pacific and Caribbean islands; also Australia's Great Barrier Reef.

Episodic inundation results from storm surges, which are anomalously high tides produced by a combination of low atmospheric pressure and wind-driven waves, especially if superimposed on astronomical high tides. Sea level varies inversely with atmospheric pressure by 1 cm/mb. Variation in wind speed also alters sea level, particularly in shallow water, due to the effects of changes in wind stress on wave

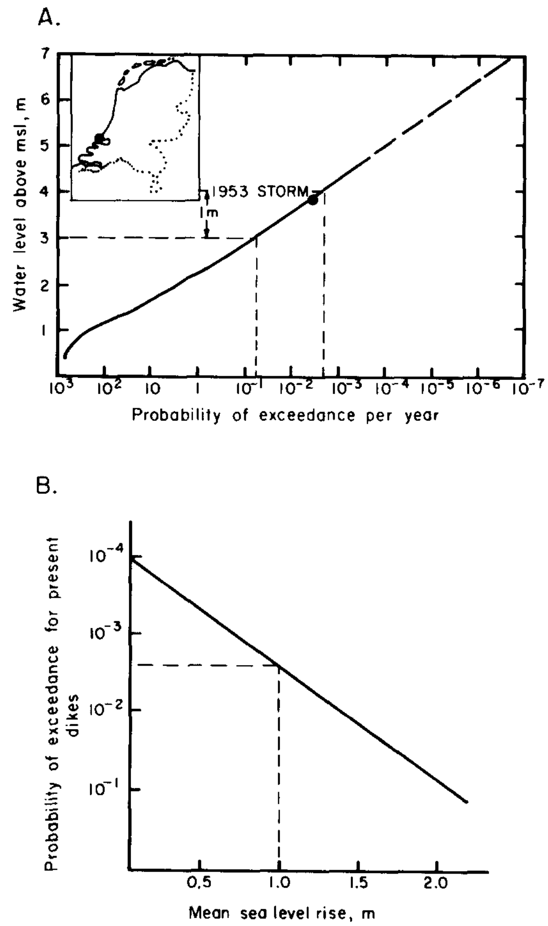

Fig. 2A. Storm surge water levels for Hoek van Holland, the Netherlands (inset, top left). The storm surge for the 1953 storm is shown for comparison. A storm surge of this magnitude (~ 4 m) occurs with a frequency of around once every 250 years, at present sea levels. (after Goemans, 1986). B. Curve of mean sea level rise vs. probability of exceedance of storm surge levels, for present dikes, central Netherlands (after Goemans, 1986).

heights. A great deal depends on fetch and aspect (facing direction).

Coastal engineers and planners calculate standard recurrence intervals of storm tides above present mean sea level. A rise in mean sea level will result in a greater frequency of occurrence of a storm surge at a given height. For example, a 4 m surge is calculated to occur at Hoek van Holland, on average once in around 250 years (Fig. 2a). If sea level were to rise by 1 m, a surge of only 3 m would be needed to reach the 4 m water level. The 3 m surge has a frequency of occurrence of approximately once in 50 years. Possible changes in tidal range, storm frequency, and storm tracks may require revision of present surge recurrence curves.

Presently, dikes in the Netherlands are designed to withstand a storm surge level with a probability of occurrence of 1/10,000 in the central part of the country, and 1/4000 in the north and south. However, a SLR of +1 m would increase the probability of exceedance from 1/10,000 to 1/250 (Goemans, 1986; Fig. 2b). Therefore, Dutch law now provides for rebuilding the dikes, in response to future increases in sea level.

Erosion

Even at present rates of sea level rise, over 70% of the world's sandy beaches are retreating (Bird, 1985). However, the worldwide erosion can be attributed to numerous factors in addition to SLR (Bird, 1988). Beach erosion is frequently intensified by anthropogenic intervention, such as by intercepting silt and sand by upstream reservoirs (e.g. the Aswan dam, Smith and Abdel-Kader, 1988), interruption of littoral drift by breakwaters, or beach sand mining.

The rate and extent of coastal erosion is expected to intensify as a result of increased SLR. The "Bruun Rule" is widely used to predict the shoreline response to SLR. It states that a typical concave-upward beach profile erodes sand from the beachface and deposits it offshore, so as to maintain constant water depth (Fig. 3; Bruun, 1962, 1983). Limitations of its applicability include fulfillment of the assumption of equilibrium conditions, with no transport of sediment into and out of the study area, and difficulty in defining the offshore limit of sediment transport. Also unaccounted for are processes such as thinning of barrier islands (Leatherman, 1983), or washover and inlet sedimentation, which could represent up to 62% of the total erosion (Fisher, 1980). Dean and Maurmeyer (1983) have extended the Bruun Rule to barrier island systems that retreat landward by filling in on the bay side to maintain constant width, as they erode on the ocean side. This model may not apply to very high rates of SLR, as is occurring presently in Louisiana (~ 10 mm/yr), where barrier islands have decreased in area by 37%, between 1890 and 1979 (Sallenger et al., 1987).

A three-dimensional sediment budget analysis (Everts, 1985) incorporates landward transport of eroded sediment, and adjusts for particle size. Kriebel and Dean (1985) have developed a dynamic equilibrium model, in which the theoretical beach profile will evolve toward a new equilibrium shape, in the face of SLR, or increased wave heights. Sand transport is assumed to maintain constant volume. Mehta and Cushman (1989) further contrast kinematic and dynamical modeling approaches.

In some cases, projection of historical shoreline erosion with respect to local sea level changes may be the most feasible approach to predicting future trends. While less quantitative than the

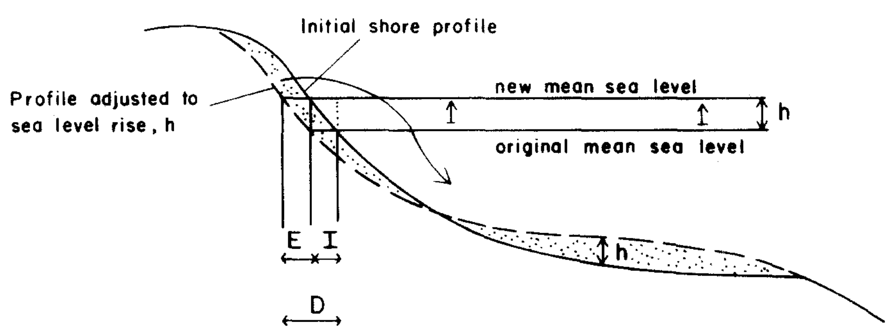

Fig. 3. Schematic illustration of the shoreline response to sea level rise, according to the "Bruun Rule". h = sea level rise, D = total shoreline displacement, I = component of shoreline displacement due to direct inundation, E = component of shoreline displacement to erosion.

above-cited models, this method accounts for the inherent variability of shoreline response, based on varying coastal geomorphology, beach composition and exposure to waves and tides. The technique has been applied to Galveston Bay, Texas (Leatherman, 1984) and Ocean City, Maryland (Leatherman, 1985).

Another approach to the assessment of future shoreline changes is to use the post-glacial marine transgression (~ 16,000–6000 yr B.P., Fairbanks, 1989) as an analog, because of similarities in rates of SLR. Thom and Roy (1988) find that coastal evolution, among other factors, is also closely linked to the gradient of the equilibrium shoreline profile. They identify two basic responses to the post-glacial marine transgression in SE Australia. The first, on very low-gradient coasts, is a landward migration of sand barriers during SLR ("rollover"), followed by dune accretion, as SL stabilizes. The second, more prevalent on higher gradient coasts, is transport of sand offshore, in accordance with the "Bruun Rule".

Sediment supply and breaker-wave height also modify the adjustment of the shoreline to the post-glacial marine transgression (Orford, 1987; Short, 1988). At high rates of SLR, but low sediment supply, other factors remaining constant, the shoreface will erode and shift landward, as for example, the barriers along the Delaware coast, during the Holocene (Kraft et al., 1987). At reduced rates of SLR, with sufficient sediment supply, seaward progradation can occur (Fig. 4; after Orford, 1987). Examples of prograded beach ridges that formed after the deceleration of the post-glacial transgression, creating a "stillstand" ($\leq$ 6000 yr B.P.), include the German North Sea Coast (Streif, 1989); the Netherlands (Jelgersma, 1979); and eastern Australia (Short, 1988; Chappell, 1987). However, within the last few thousand to hundred years, seaward deposition has given way to erosion in numerous localities (Bird, 1985; Short, 1988; Tanner, 1988). In places, the offshore sand source has now been largely depleted, and may not be available to replenish beaches in the near future. Where the rate of SLR greatly exceeds that of sedimentation, barrier islands may drown

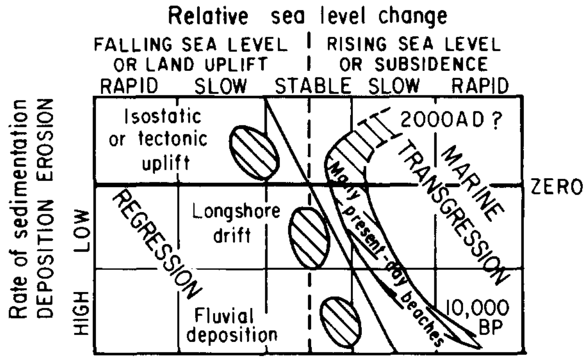

Fig. 4. Sketch illustrating the relationship between relative rates of sea level change (either rise or fall) and sediment supply to the beach (erosion or deposition), which will determine the prevalence of marine transgression or regression (modified from Orford, 1987).

in place (for example, the present Louisiana coast). However, drowning may also occur where sediment influx retards barrier migration, or where the interaction of various coastal processes results in a dynamic equilibrium of the barrier position (Carter, 1988).

Saltwater intrusion

Another inpact of rising sea level is that of increasing saltwater Intrusion into rivers and estuaries, and also infiltration into coastal aquifers. The upstream penetration of saltwater will be similar to that which occurs at present during extreme droughts, when river runoff is diminished. Higher estuarine salt levels would also contaminate urban surface water supplies. For example, a SLR of 0.73 m cause the salinity level of the Delaware River, at the intake station above Philadelphia, to exceed New Jersey's drinking water standard (50 mg/l Na^+) during 15% of the tidal cycles, while a SLR of 2.5 m would cause this value to be exceeded over 50% of the cycles (Hull and Titus, 1986).

In some major tropical deltas with seasonally fluctuating river discharge (particularly in SE Asia), fresh and saline conditions alternate within a broad zone. Reduced runoff in the dry season causes tidal penetration of saline water, forcing a fallow period in agriculture. Freshwater flooding during the wet season desalinizes the zone, which can then be used for a single wetland rice crop (Brinkman, 1984). As sea level rises the tidal saltwater zone will penetrate further upstream. This zone therefore becomes unfit for tidal swamp rice cultivation, over a longer period of the annual cycle.

In humid, equatorial climates, gradual SLR would cause the brackish-water zone, occupied chiefly by mangrove, to migrate inland. Peaty soils, formed under mangroves, tend to accumulate pyrite, which will be oxidized and acidify the soil, once the mangroves are cleared for cultivation. The encroachment of the brackish zone, with its potentially acid soil, will come at the expense of land currently suitable for economically important crops such as wetland rice, sugarcane or rubber (Brammer and Brinkman, 1990).

Sea level rise will also promote saltwater intrusion into coastal aquifers. Along barrier coasts, volcanic, and coral islands, a freshwater lens overlies saltwater. According to the Ghyben-Herzberg-Dupuit model, the freshwater lens is forty times thicker than the elevation of the water table above mean sea level. Thus, each increment of SLR will reduce the freshwater capacity by 40 times. On many low coral atolls, less permeable semi-lithified Holocene sediments typically overlie a highly permeable Pleistocene karstic subsurface, through which seawater can infiltrate. A much broader transition zone of mixed fresh and saline water underlies the freshwater lens, thereby reducing the potential freshwater storage capacity of the aquifer from that suggested by the above-cited model (Buddemeier and Oberdorfer, 1989). Any coastal erosion accompanying future SLR would further reduce the freshwater storage, with serious consequences for the water supplies of small islands and coastal dune areas. Excessive freshwater pumping has already provoked an upward migration of the saltwater–freshwater interface in many coastal localities.

A large part of Holland presently lies below mean SL, so that saltwater seeps upward into the subsoil, via groundwater flow. This problem already affects agriculture, especially during dry summers (De Ronde, 1989). Increasing SL will steepen the saltwater–freshwater gradient, and hence increase seepage, requiring additional flushing of the polders with freshwater. An analogous situation can be anticipated for the Stockton–Sacramento agricultural district, California, where much of the land is also at or below present sea level (Smith and Tirpak, 1988).

Coastal hazards and impact studies

Studies of coastal hazards, or vulnerability, delineate risk factors and estimate their relative magnitudes, extent, and likelihood of occurrence. A hazard analysis provides a baseline of present (and historical) data from which future trends can be extrapolated. However, future trends may differ substantially from those of the recent past. From a slightly different perspective, impact studies examine physical and/or socio-economic consequences of an assumed SLR scenario, based on temperature increases from general circulation models (GCM's; e.g. Hansen et al., 1988), and assumptions of ocean heat diffusion, and increases in polar icesheet melting. Some examples of studies using both approaches, on regional to international scales are-presented in the following pages.

Coastal hazard studies

Existing coastal hazards have been mapped for the U.S. (Kimball et al., 1985), including dangers from storms, waves, erosion, also landslides and earthquakes. Professor R. Dolan (University of Virginia) is currently preparing a more detailed hazards evaluation of both the East and West Coasts (pers. comm., 1990).

The Geological Survey of Canada is implementing a Coastal Information System (CIS), which will provide a national coastal inventory of geology, geomorphology, offshore characteristics, and wave, tide and surge records (Fricker and Forbes, 1988).

Coastal hazard zones in New Zealand are being mapped in order to mitigate exposure to natural hazards by appropriate land use planning (Gibb, 1984). Factors considered include historical shoreline fluctuations, lithology, beach sediment supply, landslides, neotectonic activity and storm frequency and flooding potential.

The CORINE project (Quelennec, 1989) evaluates coastal erosion risks in 11 European Community countries. It contains information on the morphosedimentologic characteristics of the coastal zone, shoreline displacement trends, and presence on absence of coastal defense works. Beach erosion occurs in all countries, especially in Portugal, France, Greece, Belgium and the Netherlands, where as much as 40–50% of the sandy beaches are retreating.

Dr. S. Jelgersma, Geological Survey of the Netherlands, is preparing a computerized data base for the UN FAO, which will include information on geomorphology, coastal sediment transport, vertical movements, vegetation, land use, suspended river sediment and discharge, tidal ranges, frequency and severity of cyclones of hurricanes (S. Jelgersma, pers. comm., 1989). The results will be represented on a 1 : 5,000,000 scale map.

Impact studies

A U.S. EPA study examines regional and national impacts (Smith and Tirpak, 1988). The study projects a loss of 13,200–26,700 km^2 of drylands without shoreline protection, assuming 1 m SLR by 2100. Under these conditions, 26–66% of the wetlands would be inundated. Shoreline protection measures for densely developed areas could cost $73–111 billion. Louisiana, the Gulf Coast, and the mid- to south Atlantic coasts will be most severely affected.

The ARIS (Australian Resources Inventory System) data base contains information on geology, landforms, vegetation and land use for each of 3027 10 by 3 km sections (Galloway et al., 1984). Priority areas (Brisbane, Sydney and the NSW North Coast) have been selected for detailed SLR impact studies, based on coastal population densities, and risk from inundation, erosion and storm flooding (Cocks et al., 1988).

Milliman et. al. (1989) have analyzed impacts of rising sea level on the Nile and Ganges-Brahmaputra deltas. They conclude that under SLR scenarios of 2.6–3.3 m (including local subsidence, damming), by the year 2100, between 21.5–26% of the habitable land in the Nile delta would be lost, and 19–24% of the population displaced, with a comparable loss in the Gross Domestic Product. In Bangladesh, due to higher rates of local subsidence, SLR could reach 3.3–4.5 m by 2100, drowning 26–34% of the land area, displacing 27–35% of the population, and causing a loss of 22–31% of the GDP, in the affected area (Milliman et al., 1989).

A preliminary impact study for the Netherlands (Jelgersma et al., 1987) points out that 57% of the population today lives below present mean sea level. Industrial and agricultural activities are concentrated on land below 5 m elevation. Even a modest SLR of 0.5 m will upset the intricate water management system in the area behind the coastal dunes and sea dikes, unless steps are taken to raise and adapt the surrounding dikes. Goemans (1986) has estimated the costs of raising the dikes to protect against a 1 m SLR at $4.4 billion, and $8.8 billion for a 2 m SLR.

The Netherlands in cooperation with UNEP has prepared a report on the "Impact of Sea Level Rise on Society" (ISOS; UNEP and Delft Hydraulics, 1989). Data for 10 priority areas [1] have been compiled on cyclone and hurricane flood damage, soil types, sensitive ecosystems, such as wetlands, mangroves, and coral reefs, and population density.

A joint United Nations UNEP-UNESCO Intergovernmental Oceanographic Commission (IOC) program is investigating the implications of climate change in five regions (Caribbean, central-east Atlantic, western Pacific, southwest Atlantic and the central Indian Ocean). An important component of this undertaking includes comprehensive reviews of coastal changes, sea-level variations and impacts on coastal ecosystems. (C. Latouche, IOC consultant, Paris; M. Hendry, 1989, U. West Indies, pers. comm).

[1] These areas are Bangladesh, Egypt, Indonesia, Maldives, Mozambique, Pakistan, Senegal, Surinam, Thailand and Gambia.

The coastal hazards data base

A coastal hazards data base is being developed to provide a global overview of the relative vulnerabilities of the world's coastlines to inundation and erosion hazards associated with accelerated SLR (Gornitz and Kanciruk, 1989).

The data base integrates information on seven variables, including: (1) relief (elevation), (2) lithology (rock type), (3) coastal landforms geomorphology, (4) vertical land movements (relative sea level changes), (5) horizontal shoreline changes (erosion or accretion), (6) tidal ranges, and (7) wave heights. Although not specifically dealt with here, data on storm frequency and intensity have been collected by others at ORNL, in a related study. Storm surges and sediment transport, although also important factors, have not been included at the present time. However, as the data are incorporated into a Geographic Information System (GIS), these layers can be added as information becomes available. The GIS approach also allows eventual integration with other climatological and socioeconomic data sets.

Here, we briefly discuss the methodology of constructing the data base, and its application to the East Coast, U.S.A., as a test case. We then evaluate the differential vulnerability of the East Coast, in terms of the individual variables and the combination of these into a Coastal Vulnerability Index. Procedures are still under development, and the outline presented here provides a demonstration of the approach rather than a final assessment.

TABLE 1

Coastal risk classes

Variable	Rank				
	Very low 1	Low 2	Moderate 3	High 4	Very high risk 5
Relief (m)	≥ 30.1	20.1–30.0	10.1–20.0	5.1–10.0	0–5.0
Rock type (relative resistance to erosion)	Plutonic Volcanic (lava) High-medium grade metamorphics	Low-grade metamor. Sandstone and conglomerate (well-cemented)	Most sedimentary rocks	Coarse and/or poorly-sorted unconsolidated sediments	Fine unconsolidated sediment Volcanic ash
Landform	Rocky, cliffed Coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Salt marsh Coral Reefs Mangrove	Beaches (pebbles) Estuary Lagoon Alluvial plains	Barrier beaches Beaches (sand) Mudflats Deltas
Vertical movement (RSL change) (mm/yr)	≤ −1.1	−1.0–0.99	1.0–2.0	2.1–4.0	≥ 4.1
	Land rising ←		within range of eustatic rise	Land sinking	→
Shoreline displacement (m/yr)	≥ 2.1	1.0–2.0	−1.0– +1.0	−1.1– −2.0	≤ −2.0
	Accretion ←		Stable →		Erosion
Tidal range m (mean)	≤ 0.99	1.0–1.9	2.0–4.0	4.1–6.0	≥ 6.1
	Microtidal ←		Mesotidal →		Macrotidal
Wave height, m (max.)	0–2.9	3.0–4.9	5.0–5.9	6.0–6.9	≥ 7.0

Data base components and risk classes

For the purposes of this paper, a vulnerable coastline is characterized by low coastal relief, an erodible substrate (e.g. sand, unconsolidated sediment), present and past evidence of subsidence, extensive shoreline retreat, and high wave/tide energies., These attributes serve as guidelines for the ranking scheme outlined in the following paragraphs.

Among the variables considered here, relief and vertical land movements (particularly subsidence), are primarily indicators of inundation risk. As a simple means of determining relief, the average elevation of 5 latitude–longitude land data points (from ETOPO5 Gridded World Elevations, National Geophysical Data Center, Boulder, CO) aggregated into 1/4° coastal cells, represents a first-order approximation of the areal extent of inundation, suitable for a global scale. This data set, although not without problems, and at relatively coarse resolution, nevertheless represents the most complete global coverage currently available. While the elevation zone within 1 m faces the highest probability of permanent inundation, the coastal strip within 5 m of present SL is also at high risk to above normal tides from severe storm surges. The hazard decreases progressively for higher average elevations (Table 1).

Vertical land movements are obtained from relative sea level trends, from a worldwide network of ~ 1000 tide-gauge stations (Pugh et al., 1987). The eastern U.S. is covered by 33 stations (Lyles et al., 1987). The relative sea level (RSL) change at each locality includes a eustatic component (1–2 mm/yr), as well as glacioisostatic, neotectonic and local subsidence components. Subsiding areas, or those with RSL in excess of the eustatic range (> 2 mm/yr), regardless of ultimate cause, face greater inundation hazards (Table 1).

The other variables of the data base are associated with erodibility risk. Bedrock lithology, shore materials, and coastal landforms vary substantially in their resistance to erosion. A generalized scale of lithologic and geomorphologic resistance to erosion is discussed in Gornitz and Kanciruk (1989). Because these factors are difficult to quantify, they are ranked into classes of increasing risk (Table 1).

Digitized historical U.S. shoreline changes, averaged into 3′ cells, come from the CEIS data base (Dolan et al., 1983). Rates within ±1 m lie within the measurement error and are considered at relatively low risk. Shores with rates of −1 m/yr or less (more negative) are eroding, and at relatively higher risk (Table 1). Conversely, shores with rates > +1 m/yr are accreting, and at correspondingly low risk.

Waves and tidal currents actively transform the shoreline. Wave heights bare proportional to the square root of wave energy, which is a measure of the capacity for erosion. U.S. wave data come from the Wave Information Study (WIS), U.S. Army Corps of Engineers (CERC), for 166 nearshore segments at roughly 10 mi (16 km) spacing along the East Coast (Jensen, 1983). (The ranks assigned in Table 1 are based on maximum significant wave heights).

The tidal range is linked to both inundation and erosion hazards. Although a large tidal range dissipates wave energy, limiting beach or cliff erosion to a brief period of high tide (Bird, 1985), it also delineates a broad zone of intertidal wetlands, which will be most susceptible to inundation following SLR. Furthermore, the velocity of tidal currents in estuaries depends on the tidal range, as well as the asymmetry of the tidal cycle and channel morphology (Pethick, 1984). Therefore, holding these other factors constant, high tidal range is associated with stronger tidal currents, capable of eroding and transporting sediment. Therefore, macrotidal coasts (> 4 m) will be more vulnerable than those with lesser ranges (Table 1). Tide range data are listed in the annual Tide Tables (NOS, 1988).

Coastal Vulnerability Index

Because the data base comprises qualitative, as well as quantitative information, at different scales and units, each variable for each coastal segment has been assigned a rank from 1 to 5, with 5 representing the most vulnerable class

TABLE 2. Relative shorelength of landform and rock types for the east coast and subregions, USA

Landform	Percent	Beaches	Marshes
East Coast			
Rocky, glaciated coast	12.3	0.5	0.2
Estuaries	41.9	0.8	15.5
Coastal plain beach	0.8	0.5	
Barrier coast	18.2	15.0	3.1
Lagoonal coast	15.3	0.2	9.5
Glacial deposit	6.0	2.1	0.6
Reef	1.4	–	1.4
Mangrove	3.5		
Other	0.6	–	–
	100.0	18.6	30.3

Rock type	Percent
Resistant, crystalline rocks	13.2
Sedimentary rocks	10.2
Sand	31.3
Other unconsolidated sediments	45.3
	100.0

Landform	Percent	Beaches
New England		
Rocky, glaciated coast (incl. cliff)	63.4	2.9
Estuaries	10.4	–
Coastal plain beach	1.2	1.2
Barrier coast	8.6	8.5
Glacial deposits	15.2	8.3
Other	1.2	–
	100.0	20.9%

Rock type	Percent
Resistant, crystalline rocks	66.8
Sedimentary rocks	9.6
Unconsolidated sediments	23.6
	100.0

Landform	Percent	Beaches	Marshes
Mid-Atlantic states			
Estuaries	64.0	3.0	11.0
Coastal plain	0.8		–
Barrier coast	13.2	9.3	3.1
Lagoonal coast	12.3	–	11.0
Glacial deposits	9.2	2.0	1.2
Other	0.6		
	100.1	14.3%	26.3%

Rock type	Percent
Resistant, crystalline rocks	0.7
Sedimentary rocks	0.2
Sand	52.1
Mud and silt	0.8
Glacial till	0.7
Calcareous sediment	2.6
Mixed or undifferentiated	42.9
	100.0

TABLE 2 (continued)

Landform	Percent	Beaches	Marshes
Southeast Atlantic			
Estuaries	39.2	0.1	26.4
Coastal plain beach	0.8	0.8	–
Barrier coast	26.1	20.4	4.3
Lagoonal coast	22.3	0.4	11.3
Reef	3.2	–	3.2
Mangrove	7.7	–	–
Other	0.8	–	–
	100.1	21.7%	45.2%

Rock type	Percent
Sedimentary rocks	18.1
Sand	22.9
Mud, silt	4.6
Calcareous sediment	11.8
Mixed lithology	6.9
Undifferentiated sediment	35.3
Other	0.4
	100.0

(highest risk; Table 1). These individual risk classes can then be combined into a Coastal Vulnerability Index, *CVI* which can be computed as either the sum or product of the variables. The product has the advantage of expanding the range of values. On the other hand, it may be quite sensitive to small changes in individual ranking factors. Therefore, it may be necessary to introduce a factor to dampen the extreme range. For the purposes of demonstration in this paper, the *CVI* is taken as the square root of the geometric mean, or the square root of the product of the ranking factors, divided by the number of variables present.

$$CVI = \left[\frac{1}{n}(a_1 \times a_2 \times \ldots a_n)\right]^{1/2}$$

where a_i = variable and n = total number of variables present.

The total range of CVI was divided into four equal parts, and the upper quarter, or $CVI \geq 33.0$ was taken as "very high risk coastline." Based on the shorelength frequency distribution, this corresponds to the 96 percentile (4% of the East Coast, including bays, lagoons and estuaries, has a *CVI* score of 33.0 or greater).

Data entry into the Geographic Information System (GIS)

The ARC/INFO GIS (ESRI, Inc.) software at ORNL can relate and manipulate data in various formats and spatial resolutions, such as (1) point data (e.g. tide-gauge stations), (2) line or arc data (lithology, landforms, waves), (3) polygons or cells (relief, shoreline displacements; Gornitz and Kanciruk, 1989). Each variable forms a feature class (coverage), which can be displayed graphically. Individual feature classes can be superposed, and areas with a common set of attributes can be identified.

Results

Estuaries represent the dominant landform along the East Coast (41.9% by length), followed by barrier coasts (18.2%), and lagoons (15.3%). Rocky, glaciated coasts occupy 12.3% of the shore, while glacial deposits form 6.0% (Table 2). Around three-quarters of the East Coast is underlain by unconsolidated sediments, the balance divided between crystalline (igneous/metamorphic) rocks (13.2%) and sedimentary rocks (10.2%), predominantly in New England (Table 2). Elevations range from a high of 100 m to near sea-level along barrier coasts. Around two-thirds of the East Coast is relatively stable (shoreline displacement within ± 1 m/yr), with 25.2% eroding and 7.7% accreting (based upon the length of coast for which data are available, Table 3). The East Coast is subsiding. Rates of sea level rise exceeding 2 mm/yr affect 89.0% of the region (Table 3). Values of CVI for the East Coast range between 1.79 and 46.29. The median value (by shorelength) is 10.12, while the upper and lower quartiles are 15.12 and 6.87, respectively. The East Coast can be divided for convenience into three regions, that also differ in geologic and terrain characteristics, described in more detail below.

New England (Maine through Connecticut)

The New England coastline consists of 63.4% strongly to weakly embayed rocky, glaciated shores. While beaches constitute 20.9% of the total New England shoreline, 39.7% of these occur on unconsolidated glacial deposits, 13.9% are pocket beaches, and 46.4% are barrier

TABLE 3

Summary of relative proportions coastal risk classes for the east coast and subregions, USA

Variable	Risk classes (percent shorelength)					
	0 *	1	2	3	4	5
East coast						
Relief	6.9	3.5	8.9	6.9	13.1	60.6
Rock type	0.2	7.4	5.8	10.2	36.3	40.1
Landform	0.4	11.0	1.5	36.6	32.8	17.7
Vertical movement	1.4	0	0.1	9.6	88.5	0.5
Shoreline displacement	49.3	2.7	1.2	34.0	6.4	6.4
Tidal range	0	45.7	33.4	20.1	0.9	0
Wave height	47.7	1.5	40.6	10.1	0	0
New England						
Relief	18.8	13.3	22.5	5.5	8.6	31.3
Rock type	1.1	36.8	30.0	9.6	9.9	12.5
Landform	0	56.5	6.9	7.6	16.3	12.7
Vertical movement	7.3	0	0.6	12.5	79.5	0
Shoreline displacement	1.4	0.5	0.6	90.7	4.6	2.2
Tidal range	0	0	29.8	65.9	4.3	0
Wave height	10.4	0	67.5	22.1	0	0
Mid-Atlantic states						
Relief	3.8	2.7	13.7	15.6	14.3	49.9
Rock type	0	0.1	0.6	0.2	43.6	55.5
Landform	0.1	0	0.4	31.4	53.9	14.2
Vertical movement	0	0	0	5.1	93.5	1.4
Shoreline displacement	53.5	1.7	0.4	24.9	11.5	8.0
Tidal range	0	59.6	38.0	2.4	0	0
Wave height	63.0	0	29.7	7.0	0	0
Southeast atlantic						
Relief	3.8	0	0	0.2	14.5	81.6
Rock type	0.1	0	0	18.1	42.5	39.3
Landform	0.8	0	0	52.8	22.9	23.6
Vertical movement	0	0	0	10.9	89.1	0
Shoreline displacement	67.8	4.1	1.9	16.4	2.7	7.0
Tidal range	0	53.8	32.2	14.0	0	0
Wave height	52.4	3.4	36.1	8.1	0	0

* No data/unclass.

beaches. Geologically, 66.8% of the New England shore is underlain largely by Paleozoic and Precambrian crystalline rocks (igneous, metamorphic), 9.6% is on sedimentary rocks, and 23.6% on unconsolidated sediments (Table 2).

In this region, 39.9% of the shore lies at an average altitude of 10 m or less (Table 3). The average regional elevation is 13.2 m, ranging from a high of 100 m, to near sea level. Only 6.8% of the coastline is eroding at rates of -1 m/yr or greater, 2.2% more than -2 m/yr (Table 3).

Tidal ranges are predominantly high microtidal to mesotidal (Table 3). There is a progressive decrease southward from northern Maine (6.1 m), to Connecticut (1.0–1.9 m), increasing again toward the western end of Long Island Sound (2.0–4.0 m). Maximum wave heights in New England are only moderately high (Table 2), with regional maxima on Martha's Vineyard (5.1 m) and Nantucket (5.2 m), off Cape Cod. The regional RSL, ranges from 1.8 mm/yr to 2.7 mm/yr.

Mid-Atlantic Coast (New York to Virginia)

The East Coast, south of New England, lies on poorly consolidated to unconsolidated Mesozoic to Holocene Coastal Plains sediments. Long Island, like Cape Cod, is formed largely of glacial moraine and outwash deposits.

The region is dominated by two major estuaries: Delaware Bay and Chesapeake Bay, both of which are river valleys submerged by the post-glacial marine transgression. The estuarine environment occupies 64% of the shorelength, with barriers and lagoons comprising only 26.3%. Unconsolidated sediments form 99.1% of the shore. Beaches occupy 14.3% of the total shore length. Of the beaches, 65.0% are located on barriers or coastal plains, 21% are along estuaries and 14.0% on glacial debris (e.g., Long Island). Marshes constitute 26.3% of the mid-Atlantic coast, 41.8% of which occur along estuaries, 41.8% are associated with lagoons and only 11.8% are on barriers (Table 2).

Elevations, in general, are lower than in New England. Here, 64.2% of the coastline is 10 m or less, and nearly half is 5 m or less. The average regional elevation is 8.9 m, ranging from a high of 70 m to near sea level. Because of the prevalence of sandy sediments and relatively mobile landforms throughout the region, nearly the entire coast is stable or eroding (Table 3). However, erosion rates are extremely variable, particularly near tidal inlets. Severe erosion (< -2 m/yr) occurs on the barrier beaches of Jones Island, NY, central New Jersey and especially the Atlantic shore of Maryland–Virginia, where several islands are retreating at rates exceeding -10 m/yr. On the other hand, some of the inlets and spits are accreting rapidly, adjacent to severely eroding beaches.

Tidal ranges decrease southward from New York toward Chesapeake Bay. Regional maximum wave heights on the open coast are moderate, ranging between 3.8 and 5.2 m.

The mid-Atlantic region is marked by above average RSL rise (> 3 mm/yr), which roughly coincides with a zone of maximum peripheral bulge collapse south of the edge of the former Wisconsin ice sheet.

Southeast Atlantic (North Carolina to Florida)

In the southeast Atlantic region, 81.8% of the shoreline lies on unconsolidated sediments; the remainder is chiefly limestone (Florida). Barriers constitute 26.1% of the total regional shorelength, lagoons 22.4% and estuaries another 39.2%, with the remainder mangroves and reefs. Marshes occupy 45.2% of the coastline, of which 58.4% are located in estuaries and 25.0% along lagoonal coasts, the remainder on reefs or backbarriers. Nearly all beaches in this region occur on barrier islands.

The southeast is the lowest region on the East Coast (av. elevation 2.13 m, ranging from 11 m to near sea level. Around 96.1% of the shoreline is 10 m or less; 81.6% is 5 m or less (Table 3).

Around 51.1% of the mapped coastline is stable (within ± 1 m), while 30.2% is eroding, and 18.7% is accreting. Although severe erosion occurs on numerous barrier beaches, north of Cape Canaveral, Florida, to the south, erosion rates

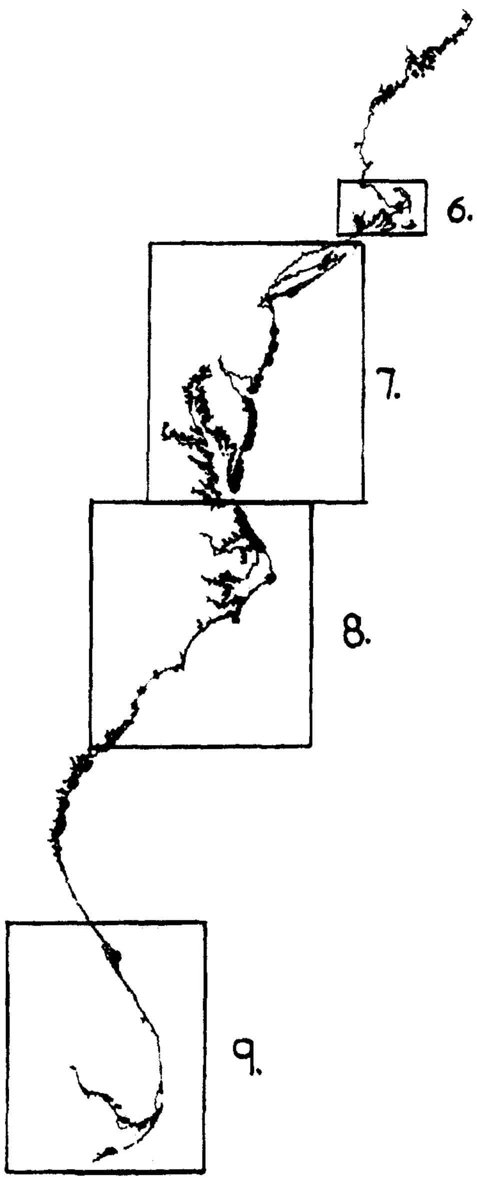

Fig. 5. The East Coast, U.S.A. Distribution of *CVI* values greater than or equal to 33.0 (heavy line). Boxed areas are shown in greater detail in Figs. 6–9.

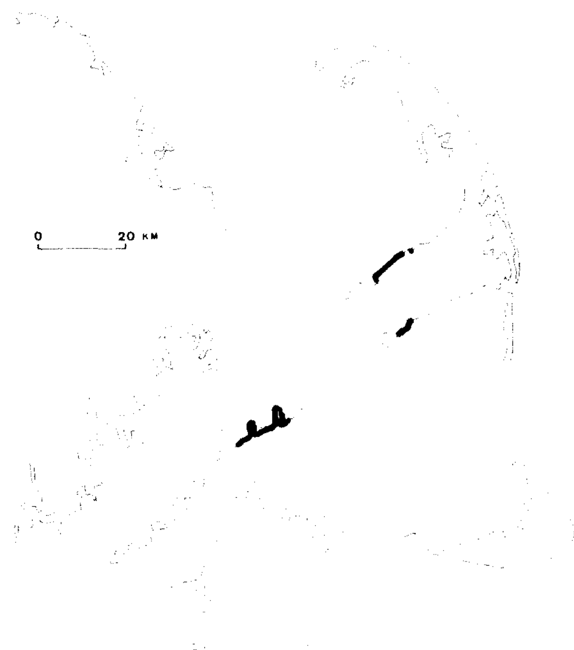

Fig. 6. Cape Cod area. Distribution of *CVI* values greater than or equal to 33.0 (heavy line).

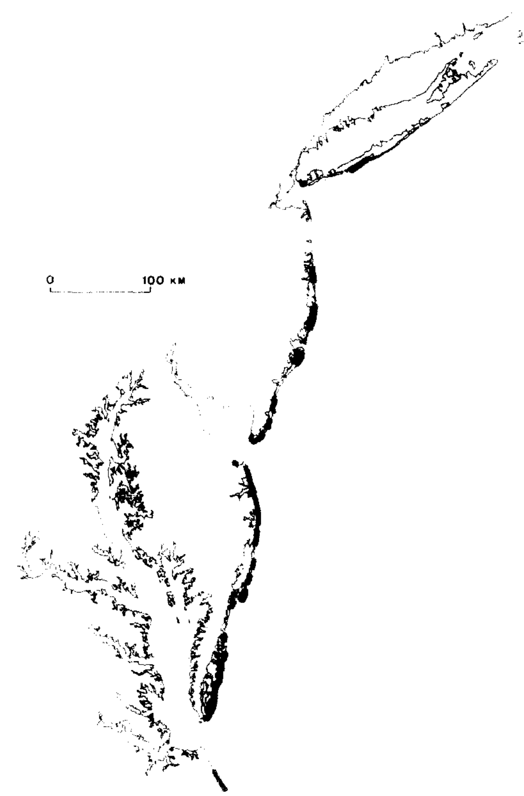

Fig. 7. Mid-Atlantic region. Distribution of *CVI* values greater than or equal to 33.0 (heavy line).

are generally fairly low. As in other regions, shoreline displacement trends are spatially highly variable. Tidal ranges grade from microtidal (< 2 m) conditions in North Carolina to mesotidal (2–4 m) conditions along the Georgia coast, and back to microtidal in Florida. Seaward shoals, off tidal inlets refract incoming waves, causing rapid erosion on one section of beach, while nearby, wave energy is reduced, and sand buildup can occur, particularly near ebb-tidal deltas (Kana, 1989).

Maximum wave heights throughout the region range between 2.4 and 5.9 m. Regional highs occur north of Cape Hatteras (5.9 m), and north of Cape Canaveral (5.1–5.2 m). Along the southeast Atlantic coast, RSL trends range between 1.8–3.4 mm/yr.

Figures 5–9 show the distribution of shorelines with *CVI* scores of 33.0 or greater for the East Coast and four selected areas: Cape Cod, the mid-Atlantic region, Cape Hatteras and Southern Florida. These composite very high risk areas occur on the Atlantic side of southern Maryland–Virginia, the northern Cape Hatteras, and also parts of the Georgia–South Carolina,

Fig. 8. Cape Hatteras–Myrtle Beach. Distribution of *CVI* values greater than or equal to 33.0 (heavy line).

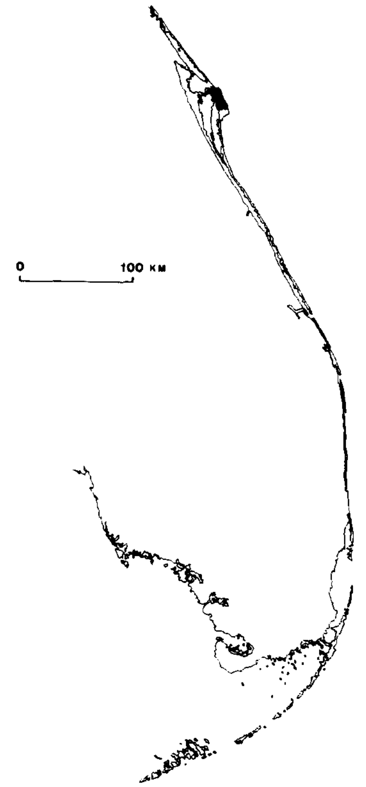

Fig. 9. Southern Florida. *CVI* values greater than or equal to 33.0.

New Jersey coasts, Cape Canaveral, Florida, and parts of Cape Cod (Gornitz, 1990b).

Summary and conclusions

Global climate warming in the next century will produce an estimated sea level rise of 0.3 to 0.9 m. Such an increase would cause inundation, both permanent and episodic, of low-lying areas, increased erosion, saltwater intrusion into coastal aquifers and estuaries and damage to man-made facilities and structures. The vulnerability of the coast to SLR will be spatially non-uniform because of variations in coastal topography, rock hardness, vertical crustal movements, wave climate and tidal regime. Low gradient coasts underlain by unconsolidated sediments, such as deltas, mudflats, barrier islands and estuaries, will be most susceptible to permanent inundation and erosion. High subsidence rates, particularly in deltaic areas, also frequently exacerbated by fluid-withdrawal at coastal cities, increase the inundation risk. Tidal marshes, mangroves and coral reefs are ecosystems most threatened by SLR. Their survival will depend on the ability of sedimentation or growth rate of plants and corals to compensate for submergence. The 1 m elevation zone will be most directly affected by inundation, but a zone of up to 5–10 m elevation could still experience some flooding due to storm surges from extreme events (hurricanes, typhoons). Defensive structures, such as dikes and sea walls, will have to be erected in many ports and coastal cities. The Dutch experience can serve as a model (Goemans, 1986).

The rate and extent of coastal erosion is expected to intensify as a result of increased SLR. However, erosion trends are not easily predicted, because of the interplay between numerous factors, including the sediment budget and oceanographic-climatic variables. Analogs for future SLR include the Holocene marine transgression (Jelgersma, 1979; Kraft et al., 1987; Short, 1988; Thom and Roy, 1988) and presently rapidly subsiding areas, such as Louisiana (Sallenger et al., 1987). Other approaches include modeling the response of beach profiles to SLR, based on historic trends (Leatherman, 1984; 1985), sediment budget analysis (Everts, 1985), and dynamic equilibrium models (Kriebel and Dean, 1985).

Studies such as those sponsored by the UNEP Regional Seas Program have begun to investigate potential adverse impacts of SLR on coastal cities and ecosystems. An international conference convened in Venice, Dec. 1989, to discuss the impact of sea level rise on coastal cities. Other impact studies cited here include the Nile and Ganges–Brahmaputra deltas (Milliman et al., 1989), U.S. wetlands (Armentano et al., 1988), and the Netherlands (Jelgersma et al., 1987). Erosion risks have been inventoried for European Community countries (Quelennec, 1989).

Preliminary statisitical summaries and data analyses have been presented for a coastal hazards data base, covering the East Coast, U.S.A. Each of seven variables, relating to coastal inundation or erosion hazards, has been assigned a rank ranging from 1 to 5, based on the relative risk factor. These risk factors are then combined into an overall coastal vulnerability index, *CVI*, here taken as the square root of the geometric mean of the risk classes. By the criteria of coastal vulnerability as defined in this study, the sections of coasts with the highest *CVI* ratings include the Atlantic coast of Maryland–Virginia, northern Cape Hatteras, parts of New Jersey, Georgia and South Carolina. Southern Florida in general does not rank as high. Although it is very vulnerable to inundation due to low elevation, and to erosion due to high risk rock types and landforms, nevertheless historic rates of erosion, wave energies and tide ranges are considerably lower than in the abovementioned areas. On the other hand, incorporation of storm frequencies, intensities and surges, as well as population densities, as additional risk factors, could very well place south Florida in the highest risk category. Extension of this data base to other regions is in progress.

Acknowledgements

This research was sponsored by the U.S. Department of Energy, Office of Energy Research, under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc. and subcontract MRETTA 19X-91348V with Columbia University. Programming assistance was provide by Mr. Jack Jia and Mr. Z.Y. Zhang. Appreciation is expressed to Mr. Robert M. Cushman and Dr. Paul Kanciruk, Oak Ridge National Laboratory, Oak Ridge, TN, and to Prof. R.W. Fairbridge, GISS, and Dr. S. Jelgersma, Netherlands Geological Survey, for their helpful suggestions and encouragement, and to Ms. Tammy W. White of ORNL for GIS data entry, analysis and preparation of coastal risk maps.

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